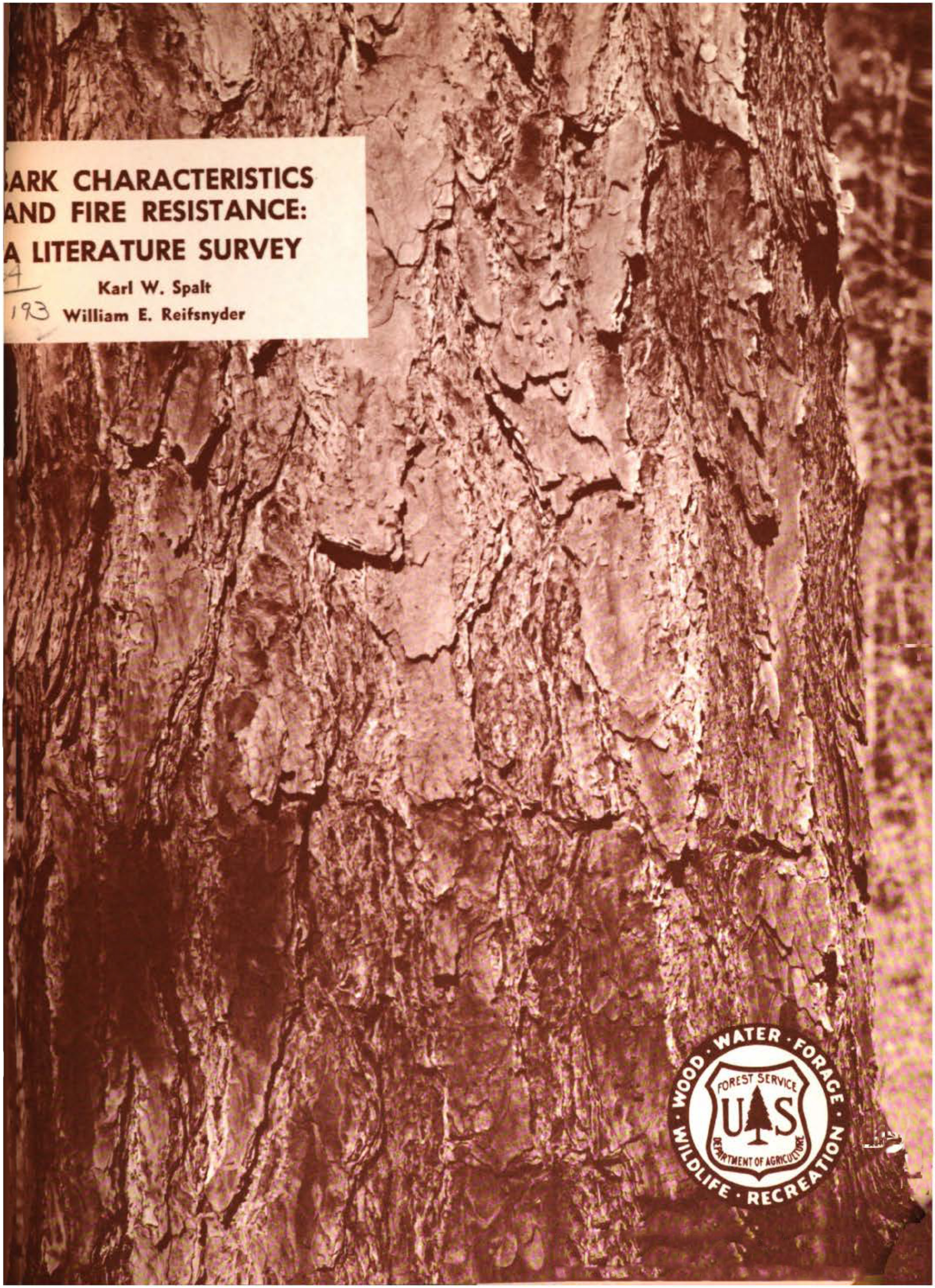
BARK CHARACTERISTICS AND FIRE RESISTANCE: A LITERATURE SURVEY

Karl W. Spalt
William E. Reifsnyder

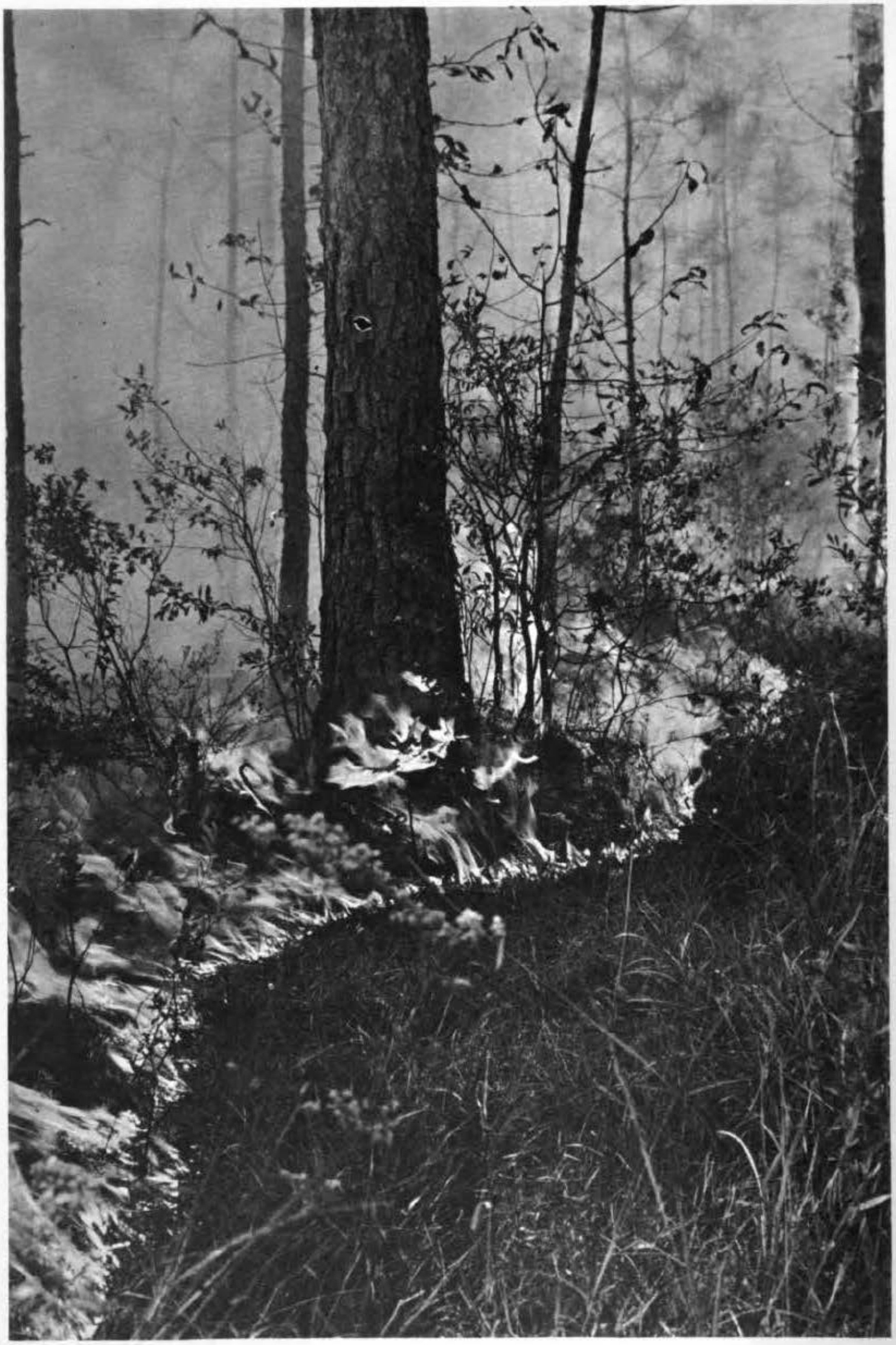


BARK CHARACTERISTICS AND FIRE RESISTANCE: A LITERATURE SURVEY

Karl W. Spalt
and
William E. Reifsnyder

Published by the
SOUTHERN FOREST EXPERIMENT STATION
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
in cooperation with
SCHOOL OF FORESTRY, YALE UNIVERSITY

Contents



BARK CHARACTERISTICS AND FIRE RESISTANCE: A LITERATURE SURVEY

Karl W. Spalt and William E. Reifsnyder[1]

It has long been obvious to foresters that trees of different ages, and of different species but the same age, respond differently to the heat of a forest fire. Ability of plants to survive a given degree of exposure to fire depends on such factors as location of heat-sensitive parts, basic nature of the protoplasm, sprouting ability, and protection afforded by insulating tissues. Although fire resistance of trees has been the subject of considerable speculation and empirical study, surprisingly little research has been done on the heat-resisting qualities of the tree's main insulating tissue, the bark. This review summarizes what is known about the characteristics of bark that govern its effectiveness as a thermal insulator.

GENERAL RELATIONSHIP BETWEEN BARK AND FIRE RESISTANCE

Most early workers restricted their attention to the subjective determination of fire resistance; their comments on possible causes were generalizations.

Lachmund (1921) subjectively ranked four western conifers in terms of their resistance to the formation of fire scars. He considered white fir[2] to be the most resistant, followed in order by Douglas-fir, ponderosa pine, and incense-cedar. He attributed the resistance of the first two species to their corky bark and low resin content; ponderosa bark is resinous, and incense-cedar is both resinous and fibrous.

Flint (1925), working in the northern Rocky Mountains, proposed that fire resistance is influenced by thickness of bark, root habit, resin content of bark, branching habit, stand habit, relative flammability of foliage, and the amount of lichen growth. Hofmann (1924) reported that when Douglas-fir was subjected to temperatures of the order of 900° F (from a slash fire), mature trees with 4-inch bark were killed after 360 minutes; 35-year-old trees with bark 1.5 inches thick were killed after 52 minutes; and 8-year-old saplings with 0.15-inch bark were killed in 1 minute.

Fritz (1932) theorized that since recurring fires reduce bark thickness in coast redwoods, any single light fire might eventually kill the cambium by heating, rather than by direct burning. He indicated that depth of the furrows as well as gross bark thickness is important, for the bark in furrows is soft, succulent, and thin.

Starker (1932), after circularizing northeastern foresters for their opinions, ranked species in order of decreasing resistance:

1. Pitch pine	12. Yellow birch
2. Chestnut oak	13. Red spruce
3. Norway pine (red pine)	14. Black cherry
4. Black oak	15. Norway spruce
5. White oak	16. Gray birch
6. Scarlet oak	17. Paper birch
7. Eastern white pine	18. Quaking aspen
8. Eastern hemlock	19. White spruce
9. Sugar maple	20. Eastern redcedar
10. Red maple	21. Northern white-cedar
11. Tamarack	22. Balsam fir

With unpublished data from A. C. McIntyre of Pennsylvania State College, Starker showed a rough correlation between bark thickness and fire resistance for several species indigenous to southern New Jersey. He also included data by O. M. Wood on mortality of trees in fire-damaged plots of the U. S. Forest Service's Allegheny Forest Experiment Station. Rankings of four oak species represented in the data of Wood and of McIntyre are shown below in comparison with the ratings indicated by Starker's questionnaire:

Fire resistance according to Starker's questionnaire	In order of increasing mortality from fire (Wood's data)	In order of decreasing bark thickness (McIntyre's data)
Chestnut oak	Chestnut oak	Chestnut oak
Black oak	White oak	Black oak
White oak	Scarlet oak	Scarlet oak
Scarlet oak	Black oak	White oak

[1]Prepared at the School of Forestry, Yale University, in cooperation with the Southern Forest Experiment Station. At the time the work was done, Mr. Spalt was a graduate student. He is now with the United States Plywood Corporation. Dr. Reifsnyder is Associate Professor of Forest Meteorology.

[2]In this review, tree nomenclature is that used by the original authors, in all cases.

In 1934 Starker subjectively correlated fire resistance and growth characteristics for species in Washington and Oregon and in the northern Rocky Mountains (tables 1 and 2).

Nelson, Sims, and Abell (1933) found yellow-poplar to be the most resistant of several southern Appalachian hardwoods. Next in order were black oak, white oak, chestnut oak,

Table 1.—*Relative fire resistance of the most important trees of Oregon and Washington in order of greatest resistance*[1]

Species	Thickness of bark of old trees	Root	Branch habit	Canopy cover	Lichen growth	Foliage inflam-mability	Most common method of killing
Western larch	Very thick	Deep	High and very open	Open	Light. Black	Low	Most resistant
Douglas fir	Very thick	Deep	High dense	Dense	0 to heavy. Grey	High	Crown fires
Yellow pine	Thick	Deep	Moder. high and open	Open	Light. Black	Low	Crown fires
White firs *concolor* and *grandis*	Moderately thick	Shallow	Low and dense	Dense	0 to heavy. Grey	Med.	Root charring and crown fires
Western red cedar (sensitive but tenacious)	Thin	Shallow	Low and dense	Dense	0 to moder. Grey	High	Root charring crown fires and burning down
Mountain hemlock	Medium	Medium low	Low and dense	Dense	0 to moder. Grey	High	Root charring and crown fires
Noble fir	Moderately thick	Medium	High and dense	Dense	Med. to heavy. Grey	High	Scorching of foliage or crowning and core burning
White pine	Medium	Medium	High and moderate	Dense	Moder. Grey	Med.	Scorching cambium or crowning
Lodgepole pine	Very thin	Deep	Moder. low and open	Open	Moder. heavy. Grey and black	Med. low	Scorching cambium or crowning
Western hemlock	Medium	Shallow	Moder. low and dense	Dense	0 to heavy. Grey	High	Root charring, crown fires and core burning
Engelmann spruce	Very thin	shallow	Low and dense	Dense	0 to heavy. Grey and black	Very high	Root charring, scorching cambium and crowning
Sitka spruce	Very thin	Very shallow	Moder. high and dense	Dense	0 to heavy. Grey and yellow	High	Root charring, occasional crowning

[1] From Starker, 1934.

and scarlet oak. McCarthy (1933) observed that young yellow-poplars with thin bark were very susceptible, while older trees with bark more than one-half inch thick had better insulation; trees less than an inch in diameter could not survive even the slightest surface fire.

Kaufert (1933) showed that trees with solid bark (such as hackberry, hickory, and red oak) had more severe scars than those with rough, corky bark (such as sweetgum and white oak).

McCarthy and Sims (1935) reported that fires usually caused greater mortality in small trees than in large ones. They doubted the existence of a straight-line relationship between tree diameter and resistance to fire because susceptibility depended both on bark thickness in relation to intensity and duration of the fire and on crown height. "As trees increase in size, the bark becomes thicker and . . . the crowns are farther removed from the fire."

Frequency of open fire wounds in trees of eastern Kentucky, according to Gustafson (1946), depended on past cutting practices, bark thickness, resistance to decay, growth rate, susceptibility to being killed by fire, and frequency and intensity of fires. Small blackgums and hickories had numerous open wounds, but the number dropped off quickly in trees above 10 inches in diameter, where thick bark developed and wounds closed readily. Elm and ash were similar to the blackgum and hickory except that elm was wounded less in the smaller classes. Oaks, tulip-poplar, and black walnut were the least injured. Gustafson drew curves relating, for 22 species, the percent of trees with open basal wounds to diameter at breast height.

Arend (1950) concluded that extreme susceptibility of eastern redcedar to fire was the

Table 2.—*Relative fire resistance of the more silviculturally important northern Rocky Mountain conifers* [1]

Species	Thickness of bark of old trees	Root habit	Resin in old bark	Tolerance: Branch habit	Tolerance: Stand habit	Relative inflammability of foliage	Lichen growth	Degree of fire resistance
Larix occidentalis	Very thick	Deep	Very little	High and very open	Open	Low	Medium heavy	Most resistant
Pinus ponderosa	Very thick	Deep	Abundant	Moderately high and open	Open	Medium	Medium to light	Very resistant
Pseudotsuga taxifolia	Very thick	Deep	Moderate	Moderately low and dense	Moderate to dense	High	Heavy to medium	Very resistant
Abies grandis	Thick	Shallow	Very little	Low and dense	Dense	High	Heavy	Medium
Pinus contorta	Very thin	Deep	Abundant	Moderately high and open	Open	Medium	Light	Medium
Pinus monticola	Medium	Medium	Abundant	High and dense	Dense	Medium	Heavy	Medium
Thuya plicata	Thin	Shallow	Very little	Moderately low and dense	Dense	High	Heavy	Medium
Picea engelmanni	Thin	Shallow	Moderate	Low and dense	Dense	Medium	Heavy	Low
Tsuga mertensiana	Medium	Medium	Very little	Low and dense	Dense	High	Medium to heavy	Low
Tsuga heterophylla	Medium	Shallow	Very little	Low and dense	Dense	High	Heavy	Low
Abies lasiocarpa	Very thin	Shallow	Moderate	Very low and dense	Moderate to dense	High	Medium to heavy	Very low

[1] From Starker, 1934.

result of its thin bark. One surface fire will usually kill redcedars, which normally have bark less than one-third of an inch thick.

PROPERTIES OF BARK

The assumption underlying all attempts to relate bark characteristics to heat injury is that the cambial layer is damaged or killed by heat received at the outer surface of the bark and conducted through the bark to the cambium. The factors determining the amount of heat received at the cambium and the temperature-time history of that layer must relate both to the properties of the bark and to the nature, amount, and duration of the heat input at the bark surface.

The properties of bark have rarely been investigated from a heat-transfer point of view (Martin, 1959), but considerable relevant information has been gathered by workers concerned with other bark-related problems. An annotated bibliography containing 1,339 references to bark has been prepared by Roth and others (1960). Another extensive bibliography was compiled by Marian and Wissing (1956-57). Hare (1961) has reviewed the physiological effects of high temperatures on living plants.

Bark varies in structure among species and families of trees, but in general it consists of secondary phloem and related tissues developed from the cambium and immediately external to it. The innermost of these tissues are living and provide for the transport of food materials along the stem. This region, primarily phloem, is loosely called inner bark, and will be so referred to in this paper. External to the phloem is a series of tissues, mostly dead and suberized, conventionally called outer bark.

Chang (1954) presents detailed information on the microscopic and macroscopic structure of the bark of North American conifers. Esau (1939, 1950) describes the development and structure of phloem. These publications are probably the best sources of basic information on the anatomy of bark.

The U. S. Forest Products Laboratory (1957) has summarized information on the chemical composition of bark. Chang and Mitchell (1955) also have investigated this subject for certain species.

Thickness

The main source of information on bark thickness is the work of mensurationists. They have found that plotting either diameter inside bark or bark thickness against diameter outside bark generally yields straight lines that pass through or nearly through the origin. However, some workers have found that the ratio of bark thickness to diameter decreases with age (Meyer, 1934) or with diameter (Meyer, 1934; Parker, 1950; Pemberton, 1924). The relationship does not seem greatly dependent on such factors as site or crown class.

Regression equations from experimental data indicate major relationship of bark thickness with d.b.h., with usually a small constant term and occasionally an age term. Table 3 presents regression equations of bark thickness against d.b.h. for several conifers. These equations have been adjusted to single bark thickness.

Table 3.—*Bark-thickness equations*

Species	Equation [1]	Source
Loblolly pine	$B = 0.241 + 0.037\,D$	Minor, 1953
Do.	$B = 0.321 + 0.043\,D$	McCormack, 1955
Do.	$B = 0.250 + 0.043\,D - 0.003\,A$	Minor, 1953
Do.	$B = 0.4679 + 0.0771\,D - 0.01176\,A$	Renfro, 1956
Pond pine	$B = 0.4906 + 0.06817\,D - 0.00735\,A$	Do.
Douglas-fir ($\leqslant$ 10 inches dbh)	$B = 0.047\,D$	Johnson, 1955
Do. ($>$ 10 inches dbh)	$B = -0.30 + 0.077\,D$	Do.
Do.	$B = -0.075 + 0.0575\,D$	Maezawa, 1956
Ponderosa pine	$B = 0.196 + 0.041\,D$	Finch, 1948

[1] B is single bark thickness in inches, D is dbh in inches, and A is age of tree in years.

A number of workers have developed factors to be applied to tree growth data to correct for increase in bark thickness. From these factors, it is possible to compute the ratio of single bark thickness to diameter, if it is assumed that the regression line passes through the origin. (This assumption would lead to significant errors only in d.b.h. classes below about 10 inches.) Table 4 presents these ratios for some eastern and western tree species.

Bark thickness may be reduced by fires. Both MacKinney (1934) and Wahlenberg (1936) found that annual or even occasional fires lessened bark thickness of longleaf pine. In annually burned saplings in the 2- to 8-inch class the reduction was about 0.033 inch.

Table 4.—*Thickness of bark as percent of d.b.h.*

Species	Pennsylvania (Chamberlain and Meyer, 1950)	Pennsylvania (Meyer, 1946)	Lake States (Gevorkiantz and Duerr, 1938)	Northern Rocky Mountains (Finch, 1948)	British Columbia (Maezawa, 1956)
Black cherry	4.8		4.0		
Red maple	3.7	3.5	3.5		
White oak	6.5	4.5	5.4[1]		
Scarlet oak	5.6	5.0	5.4[1]		
Black oak	6.5	5.0	5.4[1]		
Red pine	5.2		5.0		
Aspen	6.1		4.4	4.4	
Virginia pine	2.7				
Balsam fir	3.6		3.3		
Hemlock		4.5	5.5	3.3	
White pine		5.0	5.2	1.8	
Red oak		5.0	5.4[1]		
Chestnut oak		6.5	5.4[1]		
Beech			2.2		
Hickories			4.0		
Jack pine			4.8		
White spruce			3.1		
Tamarack			2.6		
Douglas-fir				6.7	5.8
Western larch				7.4	
Lodgepole pine				1.6	
Ponderosa pine				4.1	
Engelmann spruce				0.7	
Western redcedar				2.5	
Grand fir				4.3	
Alpine fir				1.5	
Black cottonwood				5.9	

[1] Oaks not distinguished as to species.

Stickel[3] found that the ratio of outer bark to inner bark increased with age in five eastern species, though not in beech. In a 133-year-old beech, the dead outer bark was less than one-tenth as thick as the living bark (table 5). Stickel's conclusions were:

1. The bole of pitch pine is relatively resistant to fire because its periderm is deep-seated from an early age, so that the cork layer is constantly being augmented by a great amount of large-celled phloem tissue which assumes a cork-like character.
2. The comparatively low fire resistance of beech at all ages may be attributed to a persistent superficial periderm whose activity does not produce an outer bark which exceeds the inner bark in width, and to the formation of sclerified multiseriate phloem rays which may transmit heat directly to the cambial layer.
3. The increase in heat resistance with advances in age is apparently due not simply to an enlargement in total bark thickness, but more specifically to an increase in the ratio of dead to live bark.
4. From the standpoint of bark anatomy, sugar maple and chestnut oaks should have a comparatively high resistance to fire. However, the excellent heat resistance of the bark tissue may be offset by wide, deep fissures.

Thermal Conductivity

The thermal conductivity of a substance is defined as the amount of heat that will flow through one square foot of it in one hour under a steady-state gradient of one Fahrenheit degree per foot. This property may be expressed in the units Btu/(hr ft^2) (°F/ft), or Btu/hr ft °F, and will be designated by the letter **k**.

Stickel[4] recognized that the thermal conductivity of bark might vary significantly between tree species, and that this variation might be important in determining resistance to damage by fire. He envisioned the use of a guarded hot plate for measuring thermal conductivity of bark and planned to make determinations of heat transfer through bark under simulated field conditions. Although he progressed in developing techniques for measuring the thermal conductivity of bark and obtained some preliminary measurements (discussed later), the project was ultimately abandoned (Northeastern Forest Experiment Station, 1941).

Table 5.—*Ratio of outer bark to total bark* [3]

Species and age (years)	Outer bark as proportion of total bark
	Percent
Pitch pine	
5	27
10	67
50	91
Balsam fir	
30	5
50	17
100 (estimated)	52
Eastern hemlock	
37	17
51	60
135	72
Beech	
133	9
Sugar maple	
60	50
136	67
Chestnut oak	
30	57
60	67

So far as we could determine, no numerical data on the thermal conductivity of natural bark have been published. Determinations on shredded bark, granulated cork, and cork-board are compiled in table 6, along with comparative data for common woods and woody substances and for water and air.

Thermal conductivity of wood has been shown to be linearly related to bulk density (MacLean, 1941):

$$k = 1.39\ s + 0.165$$

where s is the specific gravity, the ratio of the density of the material to that of water. The relationship was checked by Byram and others

[3] Stickel, P. W. 1936. Preliminary report on the anatomical structure of the bark of six northeastern forest trees. 25 pp. U. S. Forest Serv. Northeast. Forest Expt. Sta.

[4] Stickel, P. W. 1933. A working plan for the study of the bark character of trees in relation to their resistance to fire injury. 31 pp. U. S. Forest Serv. Northeast. Forest Expt. Sta.

(1952b) for two types of leaves (madrone and manzanita) and two types of punky wood (Douglas-fir and white fir). Agreement was judged to be satisfactory, although the experimental data were generally lower than the calculated values.

Moisture content also modifies the thermal conductivity of woody materials. MacLean (1941) presented the following relationships between moisture content of wood in percent of dry weight (m) and its thermal conductivity (including the effect of specific gravity):

$$k = (1.39 + 0.028m)\ s + 0.165 \qquad (0 < m < 40)$$
$$k = (1.39 + 0.038m)\ s + 0.165 \qquad (m \geq 40)$$

Thermal conductivity is also temperature-dependent; and for woody materials, the conductivity increases with increasing temperatures. The relationship is linear over moderate temperature ranges and can be approximated by an equation of the type:

$$k = k_0\,(1 + a\,t)$$

where k is the thermal conductivity at temperature t, k_0 is the conductivity at $t = 0$, and a is the temperature coefficient, equal to $dk/(k_0\,dt)$ (McAdams, 1954). For wood, Kollman (1951) gives

$$k_2 = k_1\,[1 + (0.0061 - 0.0054\ s)\,(t_2 - t_1)]$$

Table 6.—*Thermal and physical properties of various materials* [1]

Material	Temp. [2] (t)	Bulk density (ρ)	Thermal conductivity (k)	Heat capacity (C)	Thermal diffusivity (α)
	°F	lb/ft^3	Btu/ft hr °F	Btu/lb °F	ft^2/hr
Loblolly pine wood		29.3	0.068	0.327	0.0071 [3]
Longleaf pine wood		33.7	.077	.337	.0068 [3]
Shortleaf pine wood		28.7	.067	.327	.0071 [3]
Red pine wood		27.4	.065	.327	.0073 [3]
Charcoal	63/77	11.5	.029	.25	.0102 [3]
Cork, granulated					
Coarse	23/77	5.4	.028	.44	.0116 [3]
Fine	32/77	6.5	.025	.44	.0087 [3]
Sawdust, various	86	12.5	.034		
Shavings, various	86	8.7	.034		
Shredded eucalyptus bark	32	3.4	.029	.32	.0268 [3]
Shredded redwood bark	0/—19	4.0	.018	.215	.0203
"	100/109	4.0	.025	.246	.0268
Corkboard					
Light	0/—19	6.9	.020	.292	.0099
Light	100/109	6.9	.022	.392	.0083
Dense	121	15.7	.026		
Wood fibreboard	100/148	15.5	.028	.341	.0055
Celotex	100/109	14.4	.028	.279	.0070
Particle board	32	43.7	.102	.311	.0076
Composition board					
Madras bark	68	20.5	.041		
Erythrina suberosa bark	91	11.2	.030		
Euphorbia nioulia bark	70	16.5	.048		
Air, dry, 1 atmosphere	68	.075	.015	.24	.83
Water	68	62.3	.339	.999	.0054
To convert to cgs and °C, multiply by		.01602	.004134	1.00	.258

[1] Data from Wilkes, 1950; Dunlap, 1912; Narayanamurti, 1943; MacLean, 1941; Ward and Skaar, 1960. Data are for oven-dry specimens, so far as can be determined.
[2] Where two temperatures are given, the first refers to determination of bulk density and thermal conductivity and the second to determination of specific heat and thermal diffusivity. Since these sets of measurements were made by different workers and at slightly different temperatures, there may be slight inconsistencies in the data.
[3] Calculated from $\alpha = k/c\rho$.

where k_1 is the thermal conductivity at t_1; s is the specific gravity of the oven-dry wood; and the temperatures are in Fahrenheit. The relationship holds between — 60°F. and + 212° F.

Ward and Skaar (1960) found that their determinations of the thermal conductivity of particle board gave a somewhat greater temperature effect than was predicted by Kollman's equation. Their data indicate, however, that thermal conductivity of particle board increases linearly with temperature in the range from — 40° F to + 97° F.

Density

As indicated in the previous section, thermal conductivity of woody materials is significantly influenced by bulk density.

Computations of bark density are usually based on ovendry weight and green volume, the convention used in computing bulk density of wood.

Bark density varies widely both within and between species. Millikin (1955) found that averages of a number of eastern hardwoods and softwoods ranged from a low of 17.2 lb/ft^3 for soft elms to a high of 36.4 lb/ft^3 for maples (table 7). Values of individual trees showed a still greater range. Nishida (1946) found the range in four tropical species to be from 18.7 to 40.1 lb/ft.^{3}

Since the density of cork is about 10 lb/ft^3, it might be expected that bark density would be strongly influenced by the proportion of cork that the bark contained. In Douglas-fir, bark containing cork lunes thicker than one-quarter inch had a density of 16.2 lb/ft^3; that with cork lunes thinner than 1/32 inch had a density of 38.7 lb/ft^3 (Grondal, 1942).

Bark density may also vary with age, with size of stem on which the bark is growing, and with position on the stem. In several eastern hardwoods and conifers, Hale (1955) found that density was highest at the base and decreased toward the top; in samples from pulpwood bolts of equal diameter, the bark from the younger tree (not necessarily the younger bolt) had slightly higher density than that from the older tree. It may be that density is dependent on the growth rate of the individual pulpwood bolts, however, rather than the age of the tree. This relationship may be further confounded with position on the tree since, presumably, equal-sized bolts occur higher in older trees. Renfro (1956) found that density

Table 7.—*Bark densities* [1]

Species	Density lb/ft^3	Specific gravity
Balsam fir	30.9	0.50
Black spruce	23.8	.38
White spruce	28.3	.45
Red spruce	22.5	.36
Jack pine	33.5	.54
Poplar	36.1	.58
Birch	36.0	.58
Maple	36.4	.58
Soft elm	17.2	.28
Beech	35.1	.56
Tamarack	18.8	.30
Eastern hemlock	24.8	.40
Douglas-fir by thickness of lunes		
1/32 inch	38.7	.62
1/32 to 1/16 inch	31.2	.50
1/16 to 1/4 inch	23.7	.38
1/4 to 1/2 inch	16.2	.26
Kajoe benkoedoeng (*Wawa ceribi*)	28.1	.45
Kinar (*Manaitari*)	18.7	.30
Aikoemati	34.3	.55
White mangrove (*Laguncularia racemosa*)	40.1	.64

[1] Data for the 12 species listed first are from Millikin, 1955; Douglas-fir from Grondal, 1942; and for the tropical hardwoods from Nishida, 1946.

of bark samples from near breast height increased slightly with age (from 20 to 60 years) in pond pine, but showed no definable trend in loblolly pine. Hale's and Renfro's data are in table 8; values for other cellulosic materials may be found in table 6.

Heat Capacity

Heat capacity is the quantity of heat required to raise the temperature of a unit mass of a substance one degree with no change of state. It may be expressed in Btu/(lb °F) and will be designated by the letter **C**. It is nearly equivalent to and is often used interchangeably with specific heat, **c**, the dimensionless ratio of the heat capacity of a substance to that of water. On theoretical and experimental grounds, both are functions of temperature, increasing as the temperature increases.

Dunlap (1912), using a modified Bunsen ice calorimeter, determined the average heat capacity of a variety of domestic woods. Determinations were made with the initial tempera-

ture of 223°F and the final temperature at 32°F. The average value for 100 determinations on 20 species was 0.327. In addition, Dunlap roughly estimated the variation of specific heat with temperature by using several different starting temperatures. His equation, adjusted to the Fahrenheit scale, is

$$c = 0.245 + 0.000644\ t$$

where t is the temperature in °F.

Ward and Skaar (1960), using a method for simultaneously determining the thermal conductivity and specific heat of a material, estimated the variation of specific heat of particle board to be represented by

$$c = 0.277 + 0.00105\ t$$

This relationship was determined over small temperature differences in the range from —40°F to + 100°F.

Wilkes (1950) reports the specific heat of shredded eucalyptus bark as 0.32, and of shredded redwood bark as 0.215. Table 6 lists, as heat capacity, these values and those of other common materials for comparison.

Thermal Diffusivity

The rate at which a suddenly impressed temperature wave progresses through a material depends on an intrinsic property of the

Table 8.—*Variation of bark specific gravity with age and size of stem*[1]

Species	Age	Diameter of bolt: 3-4 inches	Diameter of bolt: 9-12 inches
	Years	*Specific gravity*	
Balsam fir[1]	61-100	0.35	0.43
Black spruce[1]	81+	.35	.44
White spruce[1]	61+	.32	.37
Jack pine[1]	80	.30	.41
White birch[1]	61-100	.48	.56
Aspen[1]	61-100	.54	.46
Pond pine[1]	20	0.30[2]	
	40	.34	
	60	.35	
Loblolly pine[2]	20	.33	
	40	.31	
	60	.33	

[1] Data for the first six species are from Hale, 1955; for pond pine and loblolly pine from Renfro, 1956.
[2] Diameter not specified. Renfro's samples were from trees in the 6-, 12-, and 18-inch classes. It is reasonable to suppose that these correspond to his 20-, 40-, and 60-year classes, but this is not stated explicitly.

material known as the thermal diffusivity. It is directly proportional to the thermal conductivity, but depends also on the volumetric heat capacity. A unit of heat flowing into a unit volume of a substance will produce a higher temperature if the substance has a low volumetric heat capacity than if its heat capacity is great. The diffusivity thus must be inversely proportional to the volumetric heat capacity, which in turn is the product of the density and the gravimetric heat capacity. Thus,

$$\alpha = \frac{k}{C\rho},$$

However, thermal diffusivity is more fundamentally defined as the parameter in the differential equation of heat conduction,

$$\frac{\partial t}{\partial \theta} = \alpha \frac{\partial^2 t}{\partial x^2}$$

where t is temperature, θ is time and x is the direction along which the heat is flowing. From either equation it can readily be seen that the dimensions of diffusivity are length^2/time, or ft^2/hr in the engineering units used. It should be remembered that the diffusivity is the ratio of several quantities and thus its dimensions are not readily interpretable in a physical sense.

Stickel's empirical determinations of heat transfer through bark under field conditions were, in fact, determinations of the relative thermal diffusivity of the bark. His procedure was described in the 1940 Annual Report of the Northeastern Forest Experiment Station:

> An apparatus was devised to determine the time required for a constant source of heat applied to the surface of freshly cut bolts to raise the temperature of the cambium to the death point. Preliminary tests were made with beech, balsam fir, and hemlock. Beech bark offers less protection than fir bark of the same thickness. The role of dead outer bark in increasing heat resistance is clearly shown by comparison of tests for balsam fir 15 inches in diameter with bark 0.4 inch thick and hemlock about 9 inches in diameter with bark 0.5 inch thick. Dead outer bark constituted about 78 percent of the total thickness in the

hemlock but only 40 percent in the balsam fir. As a result the balsam specimens were killed in about 6 minutes when a temperature of 450°C [about 840°F] was applied but the hemlock endured this heat, which badly charred and in some cases caused the bark to burn, for 12½ minutes.

Results of this portion of the investigation were published (Stickel, 1941) and are presented in table 9. Stickel's conclusions were:

> It appears that beech bark offers less protection than balsam fir bark of comparable thickness. The significance of this is increased by the fact that beech requires a longer period than balsam fir to attain any given bark thickness. Thus the tests show that balsam fir 7 inches in diameter withstood a temperature of about 300°C [about 570°F] longer than beech 12 inches in diameter.
>
> The role of dead outer bark in increasing heat resistance is clearly shown by comparison of the tests for balsam fir 15 inches in diameter with bark 0.4 inch thick and hemlock about 9 inches in diameter with bark 0.5 inch thick. Dead outer bark constituted about 78 percent of the total thickness in the hemlock but only 40 percent in the balsam fir. As a result the balsam specimens were killed in 6.8 minutes by a temperature of about 500°C [about 900°F] but the hemlock endured this heat for 13.4 minutes. Thus hemlock 9 inches in diameter is almost twice as resistant to fire as balsam fir with a diameter of 15 inches.

Similar empirical determinations by Devet (1940) have indicated that, for bark 0.20 inch thick, the descending order of heat resistance of four species was: Scotch pine, Norway spruce, sugar maple, white ash. The basis was a thousand tests in which one square inch of bark surface, exposed through a hole in a mask over a larger specimen, was heated by radiation from an electric coil to 200, 300, 400, or 500°F. The variable measured was time required for the inner surface of the bark to reach 131°F.

Renfro made 300 tests by the same technique, with external surface temperatures from 200°F to 600°F. The 131°F temperature wave passed through loblolly pine bark somewhat more rapidly than through pond pine bark of equal thickness and external surface temperature (Renfro, 1956). The regressions of time on bark thickness are in table 10.

Table 9.—*Results of "hot plate" tests for relation between bark character and resistance to fire* [1]

Avg. bark thickness (in.)	Species	Sections cut	Avg. d.o.b.	Avg. age	Tests	Avg. final temp. of heat source	Avg. time for cambium to heat to 149°F
		No.	*Inches*	*Years*	*No.*	*°F.*	*Minutes*
0.10	Balsam fir	3	5.6	40	5	572	2.64 ± 0.29
.10	Beech	3	7.2	60	6	565	2.09 ± 0.12
.15	Balsam fir	6	7.2	46	20	594	3.51 ± 0.85
.14	Beech	4	12.3	66	16	568	3.04 ± 0.59
.42	Balsam fir	3	15.2	144	13	918	6.81 ± 1.49
.51	Hemlock	2	9.4	252	5	972	13.43 ± 0.43

[1] From Stickel, 1941.

Table 10.—*Heat transfer in bark of two species of pine, according to Renfro (1956)*

Temperature of heating unit (°F)	Loblolly pine	Pond pine
200	$\log Y = -.0508 + .0743X$ [1]	$\log Y = .2221 + .0705X$
400	$\log Y = -.2019 + .0550X$	$\log Y = .0600 + .0457X$
600	$\log Y = -.1875 + .0400X$	$\log Y = -.0351 + .0371X$

[1] Y is the time in minutes for the temperature of the cambium to reach 131°F; X is the thickness of the outer bark in hundredths of an inch.

We have estimated thermal diffusivities of barks by substituting values from these empirical tests in the heat-conduction equation for a semi-infinite (i. e., infinite in one plane) homogeneous solid (Carslaw and Jaeger, 1947). From initial uniform temperature t_0 throughout the solid, the temperature t at depth x, after time θ since the surface was suddenly raised to temperature t_1, is given by

$$\frac{t-t_0}{t_1-t_0} = erfc \frac{x}{2\sqrt{\alpha\theta}},$$

in which *erfc* is the complement of the error function, and α is the thermal diffusivity.

Table 11 presents diffusivities calculated from available data by means of the above equation. When compared with established values for other materials (cf. table 6) all these estimates appear to be far too low, especially those derived from the data of Renfro and Stickel. Possible reasons for the discrepancies include (1) the finite time required to produce the desired surface temperature, (2) the likelihood that actual surface temperature was lower than that indicated by instruments, (3) the occurrence of lateral heat flow away from the small heated area, and (4) the change of state of water in the bark, which would act as a heat sink and delay the penetration of the 131° temperature wave.

Interspecies comparisons within a single worker's findings may be valid, however. In general they support conclusions as to relative heat resistance based on simple temperature-time determinations. But without further experimentation there seems to be no way to explain why Renfro's work and Stickel's yield diffusivities that are much lower than Devet's and completely out of line with those established for similar substances.

Another questionable feature of the calculated diffusivities is the apparent increase with increasing temperature. Although the thermal conductivity of woody substances increases with temperature, so also does the specific heat. Because density changes little as temperature increases, the thermal diffusivity reflects the quotient of two increasing parameters. The data of Ward and Skaar (1960) for particle board show that the two parameters increase at nearly the same rate (a slope of 0.0139 for thermal conductivity and 0.0189 for specific heat) at temperatures of about 70°F. This would indicate that the thermal diffusivity should decrease slightly with increasing temperature. It may well be that the increases shown in table 11 are spurious, the result of errors in the experimental techniques.

The presence of moisture in bark might be expected to modify ovendry diffusivity. Although the thermal conductivity of water is about five times that of dry wood, its diffusivity is slightly less. This implies a slower rate of progress of a temperature wave through moist than through dry wood. Because the change of state from liquid to vapor also requires heat, impressed high temperatures from a fire may also proceed more slowly through moist wood. Both of these effects work in the same direction—to retard the progress of a temperature wave through moist wood. However, no experimental data on these effects in bark could be found.

Moisture Content

The presence of water in the bark influences heat transfer to the cambium, but the mechanism is not clear. As bark is a woody material, it might be expected to display moisture relationships similar to those of wood. Redwood

Table 11.—*Thermal diffusivity of bark*[1] *in square feet per hour*

Surface temp. (°F)	Scotch pine	Norway spruce	Sugar maple	White ash	Pond pine	Loblolly pine	Balsam fir	Beech
600					0.00067	0.00080	0.00050	0.00059
500	0.00181	0.00181	0.00410	0.00614				
400	.00125	.00121	.00410	.00351	.00046	.00050		
300	.00102	.00049	.00289	.00397				
200					.00026	.00039		
Avg.	.00136	.00117	.00370	.00454	.00046	.00056	. . .	. . .

[1] Calculated from temperature-time data. The first four species are from Devet (1940); the next two from Renfro (1956); and the last two from Stickel (1941). Initial temperature assumed to be 70°F. Bark thickness 0.25 inch for Devet's and Renfro's data: 0.10-0.15 inch for Stickel's.

bark that had been shredded for use as insulation (Simons, 1951) had higher equilibrium moisture content than wood (U. S. Forest Products Laboratory, 1955), but the curve was essentially parallel to that for wood (fig. 1).

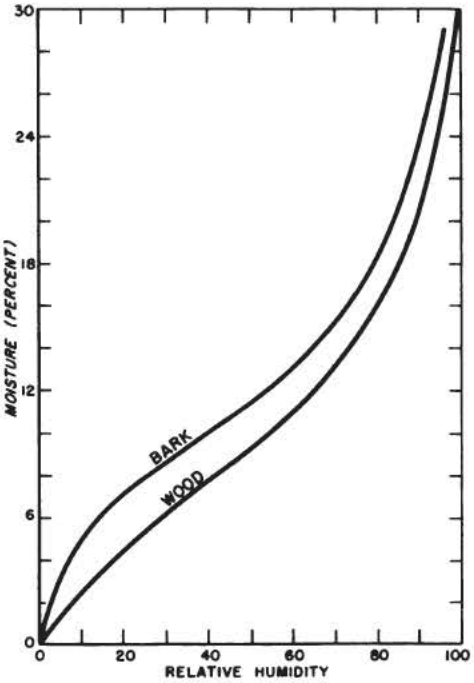


Figure 1.—*Equilibrium moisture content of bark and wood of redwood (wood at 70°F.).* (Adapted from Simons, 1951, and Forest Products Laboratory, 1955.)

At 50 percent relative humidity, equilibrium moisture contents for bark of four species of Indian trees ranged from 9.1 to 10.8 percent of the dry weight under desorption conditions (Kapur and Narayanamurti, 1934). This compares with the value of 9.1 percent for wood at 50 percent relative humidity and a temperature of 80°F (U. S. Forest Products Laboratory, 1955). Extracts from graphed data are in table 12.

Little information has been published on the time it takes for bark to reach moisture equilibrium. Because of suberization of bark cells, it might be expected that moisture transfer through the outer bark would be very slow. Kapur and Narayanamurti (1934) found that Cinchona bark from commercial sources (and presumably shredded) reached equilibrium in about 120 hours.

Moisture content of bark on living trees varies from season to season. Stickel found that the moisture in total bark (i. e., inner and outer bark taken together) of balsam fir reached a maximum in August and a minimum in March. Pitch pine bark behaved similarly, being at maximum in August and minimum during the winter. Bark of other species

Table 12.—*Equilibrium moisture content of bark of Indian trees* [1]

Species	Fiber saturation, as percent of dry weight (estimated)	Equilibrium moisture content at 50 percent rel. humid. (desorption)
	Percent	
Cinchona, *Cinchona succirubra*	24	9.5
Toon, *Cedrela toona*	22	9.1
Jaman, *Eugenia jambolana*	30+	10.8
Mango, *Mangifera indica*	27	9.3

[1] Kapur and Narayanamurti, 1934. Data estimated from curves.

showed little seasonal variation, but such trends as could be discovered were similar to those for balsam fir and pitch pine (fig. 2). A few determinations at an unspecified time of the year showed much more moisture in the inner bark than in the outer (table 13).

Gibbs (1953, 1958) found that moisture in the total bark of eight hardwoods reached a maximum in June and July, and a minimum

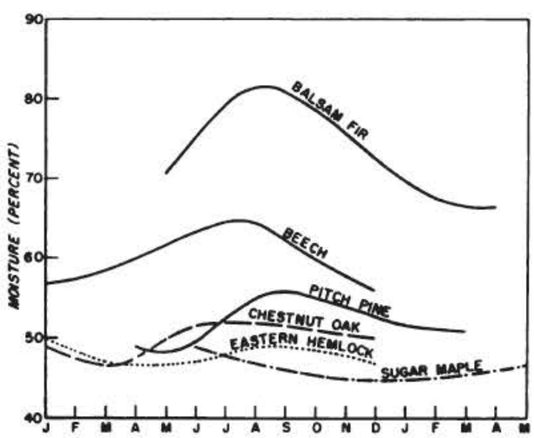


Figure 2.—*Moisture content of whole bark* (from Stickel).

in February. Figure 3 illustrates this point and also the wide variation in moisture content among species at any given time. Moisture changes in bark did not necessarily parallel those in the wood.

[4] Stickel, P. W. 1936. Preliminary report on the seasonal moisture content of the bark of six northeastern tree species. 16 pp. U. S. Forest Serv. Northeast. Forest Expt. Sta.

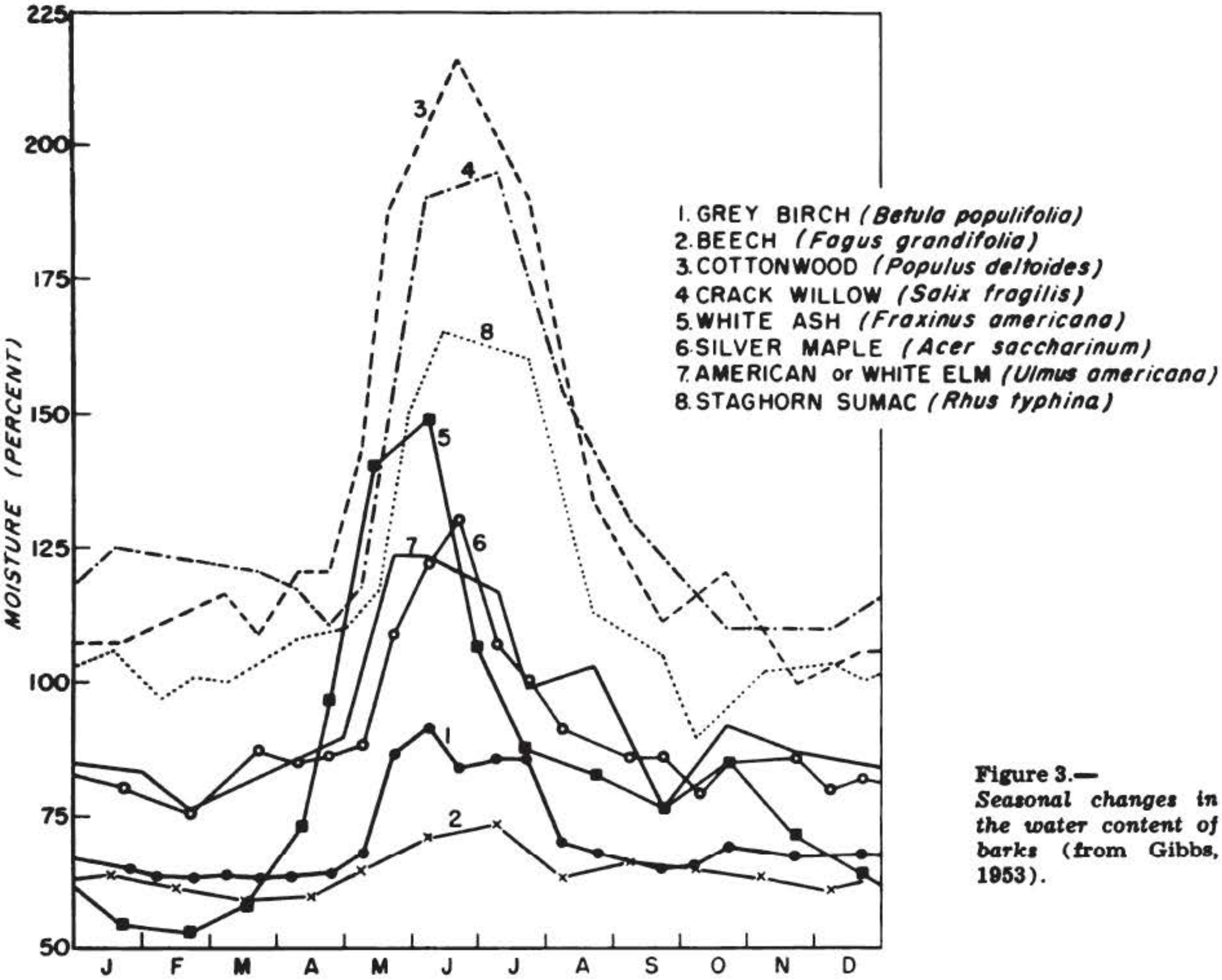


Figure 3.—*Seasonal changes in the water content of barks* (from Gibbs, 1953).

Clark and Gibbs (1957) found little variation in whole-bark moisture content of eastern hemlock throughout the year, although there was a suggestion of a maximum in the winter and a minimum in late summer (fig. 4). Differences in moisture content with location in the tree probably reflect varying proportions of inner bark to outer bark.

The same investigators found minimum bark moisture on the south side of yellow birch trees

Table 13.—*Moisture content of inner and outer bark*[1]

Species	Inner bark		Outer bark	
	Moisture content as proportion of ovendry weight	Average maximum thickness	Moisture content as proportion of ovendry weight	Average maximum thickness
	Percent	*Inches*	*Percent*	*Inches*
Chestnut oak	85.51	0.31	21.15	0.57
Sugar maple	59.65	.27	26.10	.24
Eastern hemlock	94.60	.22	25.85	.55
Pitch pine	172.91	.14	27.10	.90

[1] From Stickel, P. W. 1936. Preliminary report on the seasonal moisture content of the bark of six northeastern tree species. 16 pp. U. S. Forest Serv. Northeast. Forest Expt. Sta.

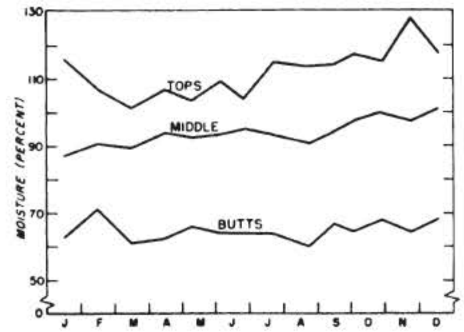


Figure 4.—*Moisture content, by section, of whole bark of eastern hemlock* (from Clark and Gibbs, 1957).

Table 14.—*Deviations of bark on south quadrant of yellow birch trees from mean moisture content (percent of dry weight) of all 4 quadrants*[1]

Date	Position in tree	Bark	Outer sapwood	Middle sapwood	Inner sapwood
		Percentage points			
January 24,1950	Top	—2.1	—6.3	—2.0	—1.8
	Middle	+ .3	—9.0	—1.1	—1.0
	Butt	—1.8	—3.4	— .3	— .5
	Tree	—1.2	—6.2	—1.1	—1.0
April 24, 1950	Top	—1.5	—7.5	—1.4	+ .9
	Middle	— .4	—6.0	+1.8	.0
	Butt	—1.8	—4.3	— .5	+2.0
	Tree	—1.2	—5.8	.0	+1.0
July 24, 1950	Top	+2.1	+ .6	— .3	— .8
	Middle	+ .4	.0	+1.6	+1.0
	Butt	— .8	+1.1	+ .9	+ .1
	Tree	+ .6	+ .6	+ .7	+ .1

[1] Clark and Gibbs, 1957. Eight trees sampled at each date.

in January, but on no definite side in summer (table 14). They attributed this to the absence of foliage in the winter, with the consequent greater heating and drying out of the sunlit bark.

Entomologists have been interested in bark moisture content because it is apparently related to development of bark beetles. According to Whiteside[4], "moisture content in twelve bark samples from infested . . . trees with normal brood development was found to average 12 percent on an ovendry basis. This condition in the outer bark was found to correspond to a relative atmospheric humidity of 56 percent." Moisture content data from other studies, as communicated by Eaton, are contained in tables 15 and 16.

Bark of lodgepole pine in Alberta (Shepherd, 1959) averaged 76 percent moisture, and ranged from 68 to 87 percent among sixteen 3-inch samples.

Greene and Marvin (1958) found that the complete bark of frozen maple twigs one inch in diameter had a moisture content of 50.11 percent of the dry weight, with a standard error of 1.03, as determined by the Karl Fischer method of alcohol extraction. Ovendrying gave a moisture content of 54.36 percent with a standard error of 0.81. Bark from twigs at 77°F had a mean of 61.84 percent with a standard error of 1.19 by ovendrying. Replicate samples from one stem gave means of 55.96 ± 0.98 percent for frozen stems, and 48.37 ± 0.63 for thawed stems.

Table 15.—*Moisture content of ponderosa pine bark (as percent of dry weight) in relation to crown position*[1]

Age class	Crown class	Moisture content
		Percent
Young (80 years)	Dominant	211
	Codominant	201
	Intermediate	190
	Suppressed	170
Immature (80-180 years)	Dominant	202
	Codominant	192
	Intermediate	180
	Suppressed	182
Mature (180-300 years)	Dominant	210
	Codominant	196
	Intermediate	182
	Suppressed	182
Overmature (> 300 years)	Dominant	214
	Codominant	198
	Intermediate	182
	Suppressed	164

[1] Personal communication from C. B. Eaton, Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, based on an unpublished report: Jeffrey, R. N. 1930. The concentration of certain sugars in the bark of the western yellow pine, as related to western pine beetle attraction. 46 pp. U. S. Bur. Ent. Div. Forest Insect Invest., Berkeley, Calif.

[4] Personal communication from C. B. Eaton, Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, quoting an unpublished report of that station: Whiteside, J. M. 1935. Temperature requirements for pupation of the western pine and mountain pine beetles.

Table 16.—*Moisture content of ponderosa pine bark (as percent of dry weight) in relation to diameter growth rate* [1]

Growth class	Width of last ring		Moisture content of inner bark
	Mm.	*In.*	*Percent*
Slow	0.10	0.004	147
	.10	.004	156
	.11	.004	136
	.27	.011	127
	.27	.011	135
	.35	.014	153
Medium	.72	.028	154
	.73	.029	185
	1.45	.057	159
	1.47	.058	140
	1.55	.061	154
	1.56	.061	163
Fast	2.07	.081	171
	3.37	.133	160
	4.25	.167	173
	5.36	.211	175

[1] Personal communication from C. B. Eaton, Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, based on an unpublished report: Beal, J. A. 1930. Phloem moisture and beetle susceptibility of western yellow pine. 6 pp. U. S. Bur. Ent. Div. Forest Insect Invest., Portland, Oreg.

In a further study the mean moisture content of the inner bark during the spring sap flow ranged from 41 percent for thawed white ash to 95 percent for frozen butternut (table 17).

Thermal Absorptivity

Thermal absorptivity of a substance is defined as the ratio of the amount of radiant energy absorbed to the total amount incident. It is a function of wavelength; with radiation from forest fires, the important wavelengths are from two to four microns—in the near infrared region.

From absorptivity measurements on weathered and fresh tree leaves and grass, Byram and coworkers (1952a) concluded that "for wavelengths greater than 2.0 microns, all fuels have approximately the same absorptivity." They did not include bark in their determinations.

In general, cellulosic materials have an absorptivity in excess of 90 percent in the region from 2.5 microns and up (Brooks, 1959). Differences in bark structure, texture, and color are therefore not likely to be associated with large differences in absorptivity. This opinion must remain tentative, for we could find no published record of measurements on bark.

Heat of Combustion

Although heat of combustion is not directly related to the rate at which heat can penetrate bark, it may have indirect significance. If bark burns and adds its own heat of combustion to that received from the surrounding fire, the heat penetrating the bark will be greater than if no bark burns. In addition, heat of combustion is related to the chemical composition of bark, which in turn may be correlated with its thermal properties (Flint, 1925).

Heat of combustion ranges from 6,921 Btu per pound for American elm bark to 10,190 for lodgepole pine bark (Chang and Mitchell, 1955). Millikin (1955) gives values as high as 10,310

Table 17.—*Moisture content (percent of dry weight) of inner bark of several hardwood species* [1]

Species	Twig sample cut	Bark removed from twig	
		Frozen (23°F)	Thawed (77°F)
		Percent	
Acer pennsylvanicum (striped maple)	Not specified	87.96	83.43
Juglans cinerea (butternut)	Flow season	95.20	66.30
Do.	Frozen	75.83	80.52
Fraxinus americana (white ash)	Flow season	43.76	41.10
Betula lutea (yellow birch)	Flow season	46.61	44.00
Do.	Frozen	65.30	48.43
Quercus rubra (northern red oak)	Frozen	75.10	72.88

[1] Adapted from Greene and Marvin, 1958.

for ovendry paper birch bark. Further data are in table 18.

CONCLUSIONS

This literature review shows that numerous workers have recognized the importance of bark characteristics in determining the fire resistance of trees. A few have measured heat transmission through bark—diffusivity, although they did not recognize it as such—and empirically estimated relative fire resistance of several species. Nevertheless, thermal characteristics of bark, for the most part, are yet to be determined. Data on heat capacity, conductivity, and diffusivity are available only for a few bark products used in the building trades and are completely lacking for bark in its natural state.

Rather good information is available on the anatomy of bark of some species. This knowledge needs to be extended and, if possible, interpreted in terms of thermal characteristics.

Thermal properties of bark are difficult to determine because they are influenced by such variables as thickness, density, moisture content, and possibly chemical composition. These variables in turn depend on species, age, and vigor of the tree, and on site, season, and current weather. Some progress has been made toward understanding these factors, but the field can still be considered wide open. And, except for thickness, no physical characteristic of bark has been related to thermal properties. Thus there is virtually unlimited opportunity for obtaining new information through both field and laboratory research on the transmission of heat through bark.

Table 18.—*Heat of combustion of bark*

Species	Moisture content	Heat of combustion
	Percent	*Btu/lb.*
Red alder	5.8	7,947
Quaking aspen	5.5	8,433
Beech	0*	7,640
Paper birch	0*	10,310
	4.8	9,434
Yellow birch	0*	9,200
	5.2	9,076
Blackgum	6.0	7,936
Cedar	0	8,610
American elm	0*	7,600
	6.7	6,921
Balsam fir	0*	9,100
	6.5	8,861
Douglas-fir	0	9,570
White fir	0	8,810
Hemlock	0	9,090
Eastern hemlock	0*	8,890
	6.2	8,802
Western larch	6.7	8,204
Soft maple	0*	8,100
Sugar maple	0*	8,230
	6.0	7,301
Red oak	4.4	8,030
White oak	6.5	6,995
Jack pine	0*	8,930
	6.6	8,761
Lodgepole pine	0	9,310
	5.6	10,190
Slash pine	6.4	9,002
Poplar	0*	8,810
Redwood	0	8,350
Spruce	0	8,740
Black spruce	0*	8,610
	6.5	8,246
Engelmann spruce	5.5	8,359
Red spruce	0*	8,630
White spruce	0*	8,530
Sweetgum	6.2	7,450
American sycamore	6.4	7,403
Tamarack	0*	9,010

* Values marked with an asterisk are from Millikin, 1955, for ovendry bark. All others are from Chang and Mitchell, 1955.

LITERATURE CITED

ARENDT, J. L.
1950. INFLUENCE OF FIRE AND SOIL ON DISTRIBUTION OF EASTERN REDCEDAR IN THE OZARKS. Jour. Forestry 48: 129-130.

BROOKS, F. A.
1959. AN INTRODUCTION TO PHYSICAL MICROCLIMATOLOGY. 264 pp. Assoc. Students Store, Univ. Calif. Davis.

BYRAM, G. M., FONS, W. L., SAUER, F. M., and ARNOLD, R. K.
1952a. THERMAL PROPERTIES OF FOREST FUELS. 34 pp. U. S. Forest Serv. Div. Fire Res.

——— FONS, W. L., SAUER, F. M. and ARNOLD R. K.
1952b. THERMAL CONCUCTIVITY OF SOME COMMON FOREST FUELS. U. S. Forest Serv. Div. Fire Res. Interim Tech. Rpt. 405, 13 pp.

CARLSLAW, H. S., and JAEGER, J. C.
1947. CONDUCTIVITY OF HEAT IN SOLIDS. 386 pp. London.

CHAMBERLAIN, E. B., and MEYER, H. A.
1950. BARK VOLUME IN CORDWOOD. TAPPI 33: 554-555.

CHANG, YING-PE.
1954. BARK STRUCTURE OF NORTH AMERICAN CONIFERS. U. S. Dept. Agr. Tech. Bul. 1095, 86 pp.

——— and MITCHELL, R.
1955. CHEMICAL COMPOSITION OF COMMON NORTH AMERICAN PULPWOOD BARKS. TAPPI 38: 315-320.

CLARK, J., and GIBBS, R. D.
1957. STUDIES IN TREE PHYSIOLOGY. IV. FURTHER INVESTIGATIONS OF SEASONAL CHANGES IN MOISTURE CONTENT OF CERTAIN CANADIAN FOREST TREES. Canad. Jour. Bot. 35: 219-253.

DEVET, D. D.
1940. HEAT CONDUCTIVITY OF BARK IN CERTAIN SELECTED SPECIES. N. Y. State Col. Forestry M. F. thesis, 83 pp.

DUNLAP, F.
1912. THE SPECIFIC HEAT OF WOOD. U. S. Forest Serv. Bul. 110, 28 pp.

ESAU, KATHERINE.
1939. DEVELOPMENT AND STRUCTURE OF THE PHLOEM TISSUE. Bot. Rev. 5: 373-432.

———
1950. DEVELOPMENT AND STRUCTURE OF THE PHLOEM TISSUE II. Bot. Rev. 16: 67-114.

FINCH, T. L.
1948. EFFECT OF BARK GROWTH IN MEASUREMENT OF PERIODIC GROWTH OF INDIVIDUAL TREES. U. S. Forest Serv. North. Rocky Mountain Forest and Range Expt. Sta. Res. Note 60, 3 pp.

FLINT, H. R.
1925. FIRE RESISTANCE OF NORTHERN ROCKY MOUNTAIN CONIFERS. Idaho Forester 7: 7-10, 41-43.

FRITZ, E.
1932. THE ROLE OF FIRE IN THE REDWOOD REGION. Calif. Agr. Expt. Sta. Cir. 323, 23 pp.

GEVORKIANTZ, S. R., and DUERR, W. A.
1938. METHODS OF PREDICTING GROWTH OF FOREST STANDS IN THE FOREST SURVEY OF THE LAKE STATES. U. S. Forest Serv. Lake States Forest Expt. Sta. Econ. Notes 9, 59 pp.

GIBBS, R. D.
1953. SEASONAL CHANGES IN WATER CONTENT OF TREES WITH SPECIAL REFERENCE TO SPECIES OF BIRCH AND TO POSSIBLE STRESS PERIODS. Rpt. of Symposium on Birch Dieback, pp. 59-69. Forest Biol. Div., Sci. Serv. Dept. Agr., Ottawa, Ontario.

———
1958. PATTERNS IN THE SEASONAL WATER CONTENT OF TREES. *In*: The Physiol. of Forest Trees, pp. 43-69. New York.

GREENE, MARY T., and MARVIN, J. W.
1958. THE WATER CONTENT OF MAPLE STEMS. Plant Physiol. 33: 169-176.

GRONDAL, B. L.
1942. DOUGLAS-FIR CORK. A PROGRESS REPORT OF A STUDY. West Coast Lumberman 69(10): 20-24.

GUSTAFSON, R. O.
1946. FOREST FIRES, BASAL WOUNDS, AND RESULTING DAMAGE TO TIMBER IN AN EASTERN KENTUCKY AREA. Ky. Agr. Expt. Sta. Bul. 493, 15 pp.

HALE, J. D.
1955. THICKNESS AND DENSITY OF BARK. TRENDS OF VARIATION FOR SIX PULPWOOD SPECIES. Pulp and Paper Mag. Canada 56(13): 113-117.

HARE, R. C.
1961. HEAT EFFECTS ON LIVING PLANTS. U. S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 183, 32 pp.

HOFMANN, J. V.
1924. THE NATURAL REGENERATION OF DOUGLAS-FIR IN THE PACIFIC NORTHWEST. U. S. Dept. Agr. Bul. 1200, 62 pp.

Johnson, F. A.
1955. Estimating past diameters of Douglas-fir trees. U. S. Forest Serv. Pacific Northwest Forest and Range Expt. Sta. Res. Note 112, 3 pp.

Kapur, S. N., and Narayanamurti, D.
1934. Hycroscopicity of tree barks. Indian Forester 60: 702-707.

Kaufert, F. H.
1933. Fire and decay injury in the southern bottomland hardwoods. Jour. Forestry 31: 64-67.

Kollman, F.
1951. Technologie des Holzes und der Holzwerkstoffe. v. 1, 1050 pp. Berlin.

Lachmund, H. G.
1921. Some phases in the formation of fire scars. Jour. Forestry 19: 638-640.

McAdams, W. H.
1954. Heat transmission. Ed. 3, 532 pp. New York.

McCarthy, E. F.
1933. Yellow poplar characteristics, growth, and management. U. S. Dept. Agr. Tech. Bul. 356, 58 pp.

———— and Sims, I. H.
1935. The relation between tree size and mortality caused by fire in southern Appalachian hardwoods. Jour. Forestry 33: 155-157.

McCormack, J. F.
1955. An allowance for bark increment in computing tree diameter growth for southeastern species. U. S. Forest Serv. Southeast. Forest Expt. Sta. Sta. Paper 60, 6 pp.

MacKinney, A. L.
1934. Some factors affecting the bark thickness of second-growth longleaf pine. Jour. Forestry 32: 470-474.

MacLean, J. D.
1941. Thermal conductivity of wood. Heating, Piping, and Air-Conditioning 13: 380-391.

Maezawa, K.
1956. Bark thickness at several heights in young Douglas-fir trees. Univ. Brit. Columbia Forest Club Res. Notes 13, 3 pp.

Marian, J. E., and Wissing, A.
1956-57. Utilization of bark. I. Index to bark literature. Svensk Papperstidning 59: 751-758, 800-805, 836-837; 60: 45-49, 85-87, 124-127, 170-174, 255-258, 348-352, 420-424, 522-523.

Martin, R. E., Jr.
1959. Stem characteristics affecting tree resistance to fire damage. A problem analysis. Univ. Mich. School Nat. Resources M. F. thesis, 45 pp.

Meyer, H. A.
1946. Bark volume determination in trees. Jour. Forestry 44: 1067-1070.

Meyer, W. H.
1934. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. U. S. Dept. Agr. Bul. 407, 64 pp.

Millikin, D. E.
1955. Determination of bark volumes and fuel properties. Pulp and Paper Mag. Canada 56: 106-108.

Minor, C. O.
1953. Loblolly pine bark thickness. La. State Univ. LSU Forestry Note 1, 2 pp.

Narayanamurti, D.
1943. The thermal conductivity and other properties of some indigenous materials. Indian Forest Rec. (n. s.) Utilization 3(2): 1-13.

Nelson, R. M., Sims, I. H., and Abell, M. S.
1933. Basal fire wounds on some southern Appalachian hardwoods. Jour. Forestry 31: 829-837.

Nishida, K.
1946. Chemical industry of wood. Tokyo.

Northeastern Forest Experiment Station.
1941. Forest fire protection. U. S. Forest Serv. Northeast. Forest Expt. Sta. Ann. Rpt. for 1940, p. 24.

Parker, H. A.
1950. Bark thickness of lodgepole pine. Canada Dept. Resources and Devlpmt. Forestry Branch Silvic. Leaflet 49, 2 pp.

Pemberton, J. E.
1924. The relation of bark to diameter and volume in redwood. Jour. Forestry 22: 44-48.

Renfro, J. F.
1956. Bark and cambium characteristics of pond pine and loblolly pine with special references to fire hardiness. N. C. State Col. M. F. thesis, 46 pp.

Roth, L., Saeger, G., Lynch, F. J., and Weiner, J.
1960. Structure, extractives, and utilization of bark. Inst. Paper Chem. Bibliog. Series 191, 446 pp.

Shepherd, R. F.
1959. Population studies of the mountain pine beetle. Interim Rpt. 1958. Canada Dept. Agr. Res. Forest Biol. Lab., 21 pp. Calgary, Alberta.

SIMONS, E.
1951. REDWOOD BARK FIBER INSULATION. Refrig. Engin. 59: 782-787.

STARKER, T. J.
1932. FIRE RESISTANCE OF TREES OF NORTHEAST UNITED STATES. Forest Worker 8(3): 8-9.

———
1934. FIRE RESISTANCE IN THE FOREST. Jour. Forestry 32: 462-467.

STICKEL, P. W.
1941. ON THE RELATION BETWEEN BARK CHARACTER AND RESISTANCE TO FIRE. U. S. Forest Serv. Northeast. Forest Expt. Sta. Tech. Note 39, 2 pp. *Also in* Pulp and Paper Mag. Canada 42: 419.

U. S. FOREST PRODUCTS LABORATORY.
1955. WOOD HANDBOOK. U. S. Dept. Agr. Agr. Handb. 72, 528 pp.

———
1957. CHEMICAL COMPOSITION AND USES OF BARK. U. S. Forest Serv. Forest Prod. Lab. Rpt. 1666-5, 10 pp.

WAHLENBERG, W. G.
1936. EFFECT OF ANNUAL BURNING ON THICKNESS OF BARK IN SECOND GROWTH LONGLEAF PINE STANDS AT MCNEILL, MISS. Jour. Forestry 34: 79-81.

WARD, R. J., and SKAAR, C.
1960. A CONTINUOUS MEASUREMENT OF THE SPECIFIC HEAT AND CONDUCTIVITY OF PARTICLE BOARD AS FUNCTIONS OF TEMPERATURE. Paper presented to meeting of the Society of Wood Science and Technology, 7 June 1960. 22 pp.

WILKES, G. B
1950. HEAT INSULATION. 224 pp. New York.